Sustainability assessment of housing developments: a new methodology

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Sustainability Assessment of Housing Developments : A New Methodology

L'évaluation de la durabilité des systèmes urbains : une nouvelle méthodologie

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Abstract

In order to combat the rapid degradation of the world's ecosystems and depletion of natural resources, governments and planning authorities are searching for more sustainable forms of development. The need to assess the "sustainability" of development proposals is thus of great importance to policy and decision makers. However, effective methods of assessing the overall sustainability of housing developments (proposed or existing) have yet to be established. This research aims to address this problem by presenting a new methodology to assess the sustainability of housing development systems. The methodology uses indicators with a common "Sustainability Scale" which is derived from percentiles of a population with resource use above a predetermined sustainable level, and has been coupled with a technique for modelling complex housing development systems using multi-agent based simulation. The methodology was shown to be operational in the case study application of the Christie Walk housing development in inner-city Adelaide, Australia. The results of the assessment showed that the development compared favourably to the rest of the Adelaide metropolitan area. The case study also highlighted, through behavioural scenario analyses, the importance of good infrastructure and design in reducing the impacts of human behaviour on housing development sustainability. It is envisaged that this new methodology of combining sustainability assessment with an integrated modelling technique will provide the basis for a solution to many of the challenges currently facing sustainability researchers, policy makers and planning authorities of urban environments both in Australia and world wide.

Résumé
Afin de combattre la dégradation rapide des écosystèmes mondiaux ainsi que l'épuisement des ressources naturelles, les gouvernements et les autorités de planification recherchent des formes de développement plus durables. La nécessité d'évaluer la «soutenabilité» des propositions de développement est ainsi de grande importance pour la politique et les décideurs. Cependant, des méthodes efficaces pour évaluer la durabilité globale des développements de logement (proposés ou existants) ne sont pas encore établies. Les objectifs de ces recherches adressent ce problème en présentant une nouvelle méthodologie conçue pour évaluer la durabilité des systèmes complexes de développement de logement. Une méthode pour évaluer des indicateurs de durabilité sur une «échelle de soutenabilité», basée sur des centiles d'une population avec l'utilisation de ressource au-dessus d'un seuil soutenable, a été développée. Cette méthode a été couplée à une technique pour modéliser les systèmes de développement complexes de logement en utilisant la simulation multi-agent. La méthodologie a été mise en pratique dans un cas d'étude du groupe de logements, Christie Walk, situé au centre-ville d'Adélaïde en Australie. Les résultats de cette évaluation ont demontré que Christie Walk est plus soutenable que la plupart de la zone métropolitaine d'Adélaïde. Les resultats des analyses de scénario montrent aussi l'importance d'une bonne infrastructure et conception des développements pour réduire les impacts du comportement humain sur la durabilité des logements. On envisage que cette nouvelle méthodologie, qui couple l'évaluation de la durabilité avec une technique de modélisation integrée, fournira une base fondementale pour résoudre plusieurs des défis auxquels font actuellement face les chercheurs en développement durable, les décideurs et les autorités de planification des environnements urbains en Australie et dans le reste du monde.

Keywords: sustainability assessment, urban development, multi-agent systems (MAS)

***Mots-clés** : l'évaluation de la durabilité, développement urbain, systèmes multi-agents (SMA)*

1. Introduction

The complexity of nature-society systems such as those of urban housing developments makes the understanding and consequent sustainability assessment of these systems difficult. A large proportion of research into sustainable development over the past fifteen years has attempted to assess various components of system sustainability without due respect for the complex interrelations between the components, which can have a significant effect on overall system behaviour (Clark and Dickson, 2003). This has led to an incomplete understanding at government and policy making levels of what is required to achieve sustainable development for all communities. A consistent framework for sustainability assessment is therefore required for decision-making purposes (Nishijima et al., 2004).

A review of current literature into the assessment of the sustainability of housing developments (Daniell et al., 2004), found that:

- Governments and planning authorities world wide require more holistic methods for sustainability assessment in order to develop future planning strategies (Tweed and Jones, 2000);
- Due to the narrow focus of current assessment tools, decision makers find it difficult to make judgments which are consistent with sustainability goals for development (Macoun et al., 2001);
- Current sustainability assessment tools do not adequately represent the temporal, spatial and behavioural aspects of sustainability;
- There is no common methodology which relates measures of resource use and other variables (referred to as indicators) to a measure of sustainability; and
- There is a specific need for a methodology that can be used to assess the sustainability of complex housing development systems (Deakin et al., 2002).

In order to address the shortcomings outlined above, a new methodology for the assessment of the sustainability of complex housing development systems is developed in this research using multi-agent simulation. The methodology couples complex systems modelling and sustainability assessment, and provides a decision-making tool that can be used by policy makers, governments and planning authorities. The application of the methodology to a case study example, Christie Walk, an Australian eco-development, is also presented, with a special focus on determining the impacts of human behaviour on the housing development's sustainability.

2. Methodology

The proposed methodological framework for the sustainability assessment of housing developments is presented in Figure 1 and explained in detail throughout this paper.

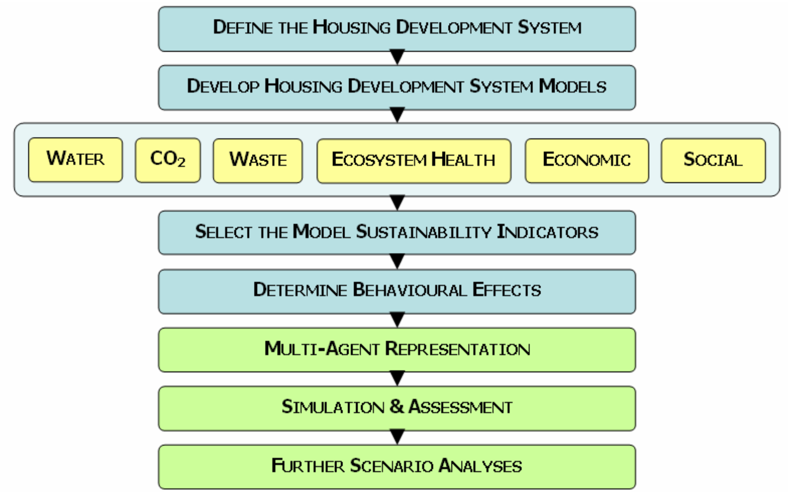

Figure 1: Housing development assessment methodology

2.1. Definition of housing development systems

A housing development is a system that can be defined, and its sustainability assessed, if the definition of sustainability presented by Gilman (1992) is adopted. Gilman stated that sustainability is:

> *"the ability of a society, ecosystem, or any such on-going system to continue functioning into the indefinite future without being forced into decline through exhaustion or overloading of key resources on which the system depends."*

Using this Gilman definition, Foley et al. (2003) outline that for a system to be sustainable, all of the resources upon which the system relies must be managed appropriately, including: natural; financial; social; and man-made (infrastructure) resources. Appropriate management requires knowledge relating to the system boundary, system resources, interactions between adjacent systems and allowable limits, or thresholds, for each resource. Each of these elements will be unique to the particular system under consideration, and each system must be assessed on its own merits. However, the process of assessment should be consistent for every system.

This general systems approach to sustainability can be applied more specifically to an urban development by viewing each urban housing development as a unique system. An example of such a system with its resources and interactions is shown in Figure 2.

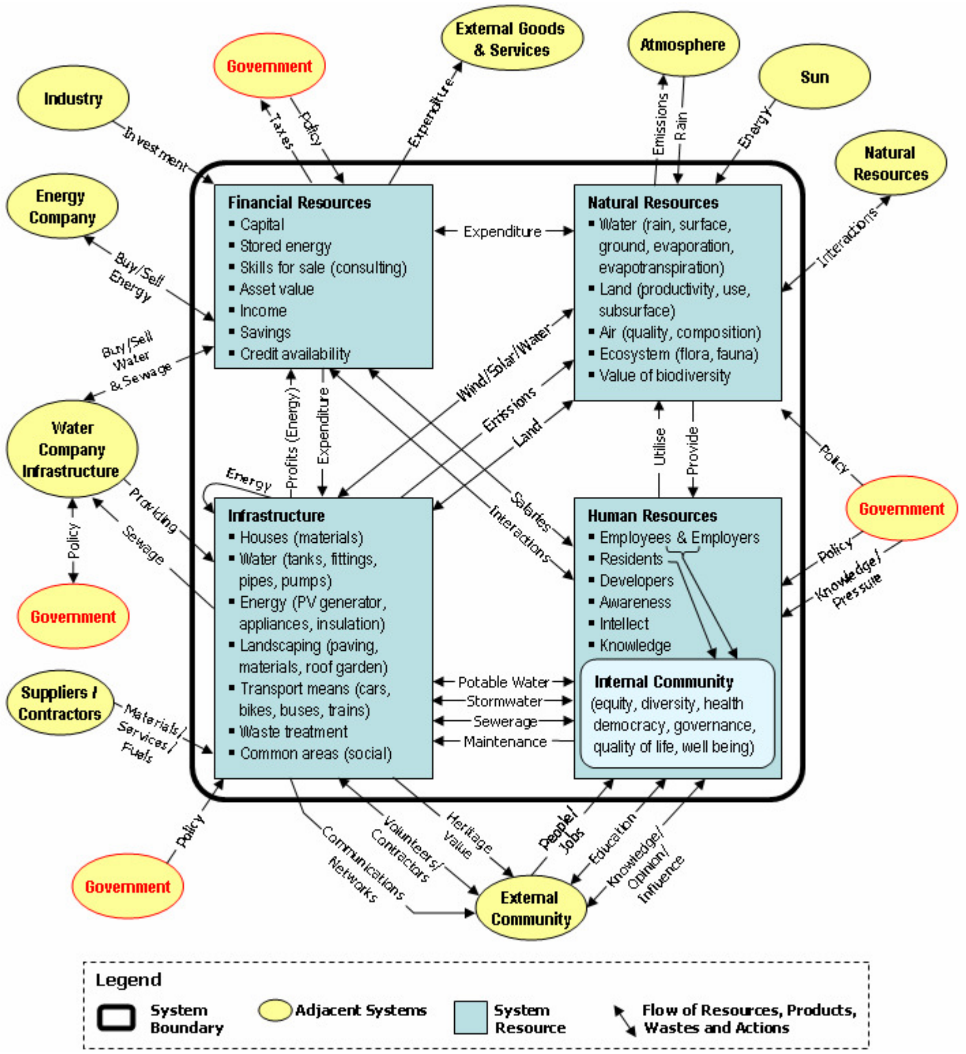

Figure 2: The complex housing development system

To assess the sustainability of a housing development, all of the resources and their interactions represented in Figure 2 (both within and external to the system) need to be determined as specified in the methodology presented in Figure 1. As outlined by Foley et al. (2003), if each resource in the housing development is considered as a state variable x_i, at any time t_j, the state of the system can be expressed for n state variables in vector form as:

$$\mathbf{x}(\mathbf{t_j}) = \{ x_1(t_j), x_2(t_j), \ldots, x_{i-1}(t_j), x_i(t_j), \ldots, x_n(t_j) \} \quad (1)$$

The changes to each state variable or resource can then be modelled over each specified time interval where $t_{j+1} = t_j + \Delta t_j$.

2.2. Housing development system models

Considering a complex urban housing development system as outlined in Figure 2, the key resources, processes and interrelations of a housing development can be defined in terms of six interrelated models, namely: water; carbon dioxide (CO_2); waste; ecosystem health; economic; and social. All of these models are affected by human behaviour and are represented in Figure 3. The role of human behaviour is discussed further in Section 2.4.

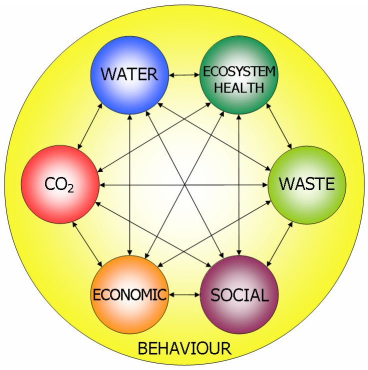

Figure 3: Framework of interrelated models for housing development sustainability assessment

In Figure 3:

- The water model incorporates all the water related processes of the development, including rainfall-runoff, infiltration and potable and non-potable water use;
- The CO_2 model accounts for both embodied and operational energy use, calculated as an equivalent mass of CO_2, which incorporates the effects of building materials, infrastructure, electricity and gas use as well as occupant transport use;
- The waste model accounts for all solid and liquid waste, both produced on site, and leaving the site, including: sewage; compost; waste to be recycled; and waste sent to landfill;
- The ecosystem health model encompasses environmental aspects of the development such as biodiversity and land use changes, as well as air and water quality.
- The economic model accounts for both the microeconomic processes of each household based on income, expenditure and corresponding levels of debt, as well as the macroeconomic processes which affect the housing development, such as inflation and interest rates; and
- The social model incorporates levels of occupant satisfaction relating to comfort, living conditions, access to services (transport, health, education, shopping), employment, as well as equity amongst occupants.

Following the methodology presented in Figure 1, for each of these models an indicator representative of the model processes and consequent sustainability must be chosen for assessment purposes[1].

2.3. Sustainability indicators and assessment

Once indicators are selected, it is important to determine the conditions under which an indicator is to be considered sustainable. Available assessment techniques for housing developments reviewed by Daniell et al. (2004a) use indicators that predominately present and collate resource use or resource quality data. There is little attempt to assess the adequacy of the data with respect to the level or condition of the resources available to the system under consideration. Foley and Daniell (2002) recognised that the use of a sustainability satisfaction scale for indicators could allow the comparison of indicators not only against each other but also against sustainability criteria. This approach, together with the system sustainability conditions outlined in Foley et al. (2003), was further developed by Daniell et al. (2004c) to create the "Sustainability Scale" for indicators, which is presented in this section.

The Sustainability Scale is based upon a probability of exceedance of the ultimate sustainability threshold level, *threshold*(x_{ij}), for each resource, $x_i(t_j)$, as shown in Figure 4.

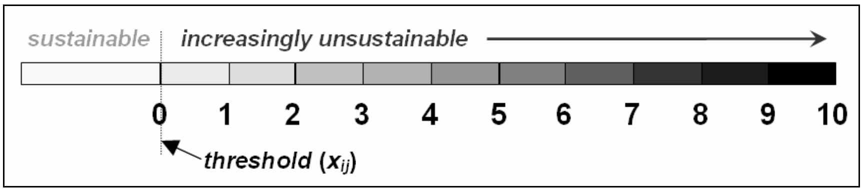

Figure 4: The Sustainability Scale

The sustainability threshold level is the resource level at which the system is deemed to be able to meet the requirements of the system while managing the resources within the system at an appropriate level, without compromising the ability of adjacent systems to be sustainable. The Sustainability Scale ranges from 0 to 10, where 0 is considered as sustainable resource usage, and the values between 0 and 10 represent increasingly unsustainable resource use. In other words, for a housing development system's resource use to be considered sustainable, Eq. 2 must be satisfied[2]:

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[1] More than one indicator could be chosen for each model if desired.

[2] The reverse may be true when a system's resource level needs to be maximised (i.e. river flows for environmental requirements).

$x_i(t_j) \leq \text{threshold}(x_{ij})$ (2)

Individual Sustainability Scale Ratings (SSRs) for indicators are based on the cumulative probability distribution of current resource usage at a larger system scale exceeding the sustainable threshold level (i.e. a probability of threshold exceedance between 0 and 1).

The larger system chosen will depend on the purpose of the sustainability assessment. For example, a housing development might need to be compared to other developments within a local council area or to other housing developments in a larger metropolitan area.

Once this larger system scale has been chosen, a distribution of the resource use of the indicator to be assessed must be developed. An example of a cumulative distribution function (in this case where the indicator is mains water use in the metropolitan Adelaide area), from which the Sustainability Scale can be derived, is represented in Figure 5.

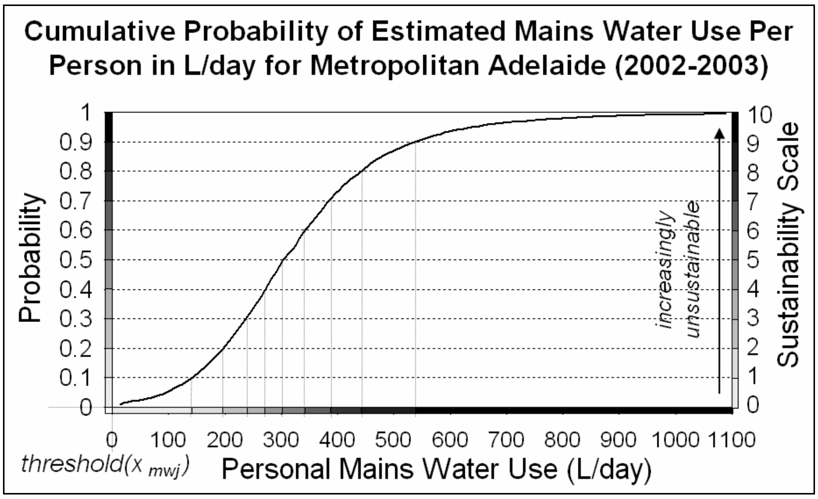

Figure 5: Cumulative distribution of mains water use exceeding the sustainability threshold level

In order to create the cumulative distribution used to derive the Sustainability Scale, a number of steps need to be undertaken, dependent on the form of data available. The example of mains water use in the Adelaide metropolitan area shown in Figure 5 will be expanded upon here to demonstrate the process.

Step 1: The frequency of people corresponding to each level of estimated mains water usage in the Adelaide metropolitan area needs to be plotted, as shown in Figure 6.

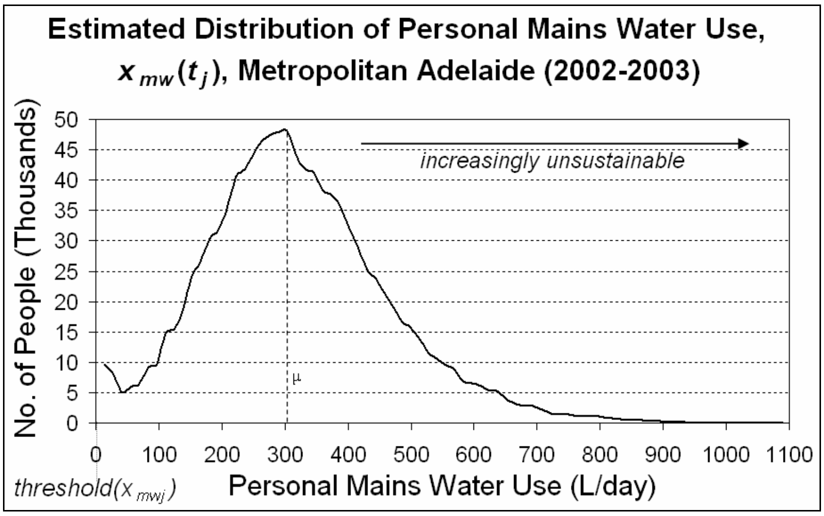

Figure 6: Mains water use frequency distribution and the sustainability threshold level

Step 2: The sustainability threshold level for the resource, in this case mains water use, needs to be defined. For a housing development scale of sustainability assessment, the threshold for mains water use is defined as 0 L/person/day[3], i.e. $threshold(x_{mwj}) = 0$ as denoted in Figure 6.

Step 3: Now consider all people with resource usage below the threshold to be sustainable and eliminate them from the distribution, in this case all people who do not use the mains water supply. This is equivalent to removing sustainability as an outcome from the original sample space.

Step 4: The probability density function of the new sample space can be calculated (corresponding to the pdf of mains water use of only people exceeding the sustainability threshold in the example). Since being in the sustainable state has been removed as an outcome and the distribution has then been normalised on the remaining outcomes (i.e. being in an unsustainable state), a conditional probability density function has been calculated. If this pdf is defined as $f(x_{ij} \,/\, x_{ij} > threshold(x_{ij}))$ (for any resource), then:

$$P\ (\ a < X \leq b \mid X > threshold(x_{ij})\ )\ =\ \int_a^b f(x_{ij} \,/\, x_{ij} > threshold(x_{ij}))dx_{ij} \qquad (3)$$

[3] This considers that for a housing development to be sustainable all water used must be collected on site if the site does not contribute to the mains water supply. Considering a different example, i.e. an urban development on an isolated island with no mains water, the threshold for water use could be set at a level that would not deplete the freshwater supplies or groundwater levels.

where: X is a random variable within the sample space [$threshold(x_{ij})$, ∞); and x_{ij} is the estimated value of resource usage of an unsustainable individual[4].

Note: The order of steps 3 and 4 is very important in order to maintain the first Axiom of Probability i.e. $\int_{-\infty}^{\infty} pdf = 1$*. The relative frequencies (no. of people / total population) must be calculated using only the portion of the population exceeding the threshold required for sustainability.*

Step 5: Calculate the cumulative distribution function, $F(x_{ij} \mid x_{ij} > threshold(x_{ij}))$, corresponding to the pdf calculated in Step 4, namely the probability density given that resource usage is in an unsustainable state:

$$F(x_{ij}) = P\,(\,X \le x_{ij} \mid X > threshold(x_{ij})\,) = \int_{-\infty}^{x_{ij}} f(x_{ij} \mid x_{ij} > threshold(x_{ij}))\,dx_{ij} \qquad (4)$$

where $x_{ij} \in [\, threshold(x_{ij})\, , \infty\,)$.
For the mains water example, the resulting cumulative distribution function is shown in Figure 5.

Step 6: The corresponding Sustainability Scale Ratings, SSRs, for a particular resource usage can now be directly calculated from the cumulative distribution function:

$$\begin{aligned} SSR &= 10 \times F(x_{ij}) = 10 \times P\,(\,X \le x_{ij} \mid X > threshold(x_{ij})\,) \\ &= 10 \times \int_{-\infty}^{x_{ij}} f(x_{ij} \mid x_{ij} > threshold(x_{ij}))\,dx_{ij} \end{aligned} \qquad (5)$$

This can be performed without any loss of generality since a sustainable development has SSR = 0 (as in a sustainable state $x_{ij} \le threshold(x_{ij})$ which leads to $P\,(\,X \le x_{ij} \mid X > threshold(x_{ij})\,) = 0$).

This Sustainability Scale can be used to measure any indicator and thus produces a uniform method of sustainability indicator assessment. For example, waste production can be measured against water use for equivalent levels of sustainability (or, more correctly, unsustainability) or the same indicators can be compared between developments in the same larger system.

The indicator assessment concept can also be viewed in terms of system vulnerability. If the resource or indicator level fails to be sustainable, i.e. for the mains water example, if $x_{mw}(t_j) > threshold(x_{mwj})$, then the magnitude of failure or *vulnerability* of the system is quantified on the Sustainability Scale.

The proposed methodology also allows for the continual assessment of system sustainability through time. For example, if a sustainability assessment is to be

[4] Here "an individual" is an abstraction that can be interpreted as one individual person within a housing development or an "equivalent average individual" of a development that can be compared to other developments within the larger community or system scale

carried out on a housing development every year for a number of years, and data are available to create the resource distributions required for the larger system used for comparative assessment for each of these years, then the Sustainability Scale of resource usage will change through time. The corresponding yearly resource use for the housing development being assessed can then be compared, based on the equivalent yearly Sustainability Scale. The threshold level of sustainability for a resource, *threshold*(x_{ij}), may also vary over time, depending on new scientific research or technological advances.

At the initialisation point, a sustainability assessment of the collection of six indicators for these models may be performed to assess the current sustainability of the housing development system. Further modelling may then be performed to assess the potential sustainability of the housing development through time.

The development of the "Sustainability Scale" for indicators is an advancement on existing assessment techniques as the indicators provide a measure of the proximity of the indicator to the sustainable or threshold level. The methodology to this point allows the assessment of sustainability at a given point in time but does not address other deficiencies in existing assessment techniques such as the effect human behaviour or changes in the system over time. The last three steps of the methodology in Figure 1 address these aspects.

2.4. Effect of human behaviour

One of the criticisms of current urban simulation techniques is the lack of sufficient behavioural theory used in the modelling processes (Waddell and Ulfarsson, 2004). This view is confirmed by the findings from the review of current sustainability assessment tools presented by Daniell et al. (2004a), which showed that the effect of human behaviour in relation to resource use and sustainability was not adequately included. It has commonly been reported that human behaviour has a significant impact on resource use (Georg, 1999), although there has been very little research to date to quantify these effects (Jalas et al., 2001). To overcome the behavioural deficiencies of previous sustainability assessment methods, human behaviour, particularly related to resource use, has been included in the sustainability assessment framework developed as part of this research.

Behaviour relating to resource use can be analysed in many ways by studying both the causes and effects of human practices and actions. Study of behavioural patterns can be related back to sociological theory, where the normative (values and preferences), cognitive (representations and beliefs), operational (practices and actions) and relational (social interaction and relationship) aspects of individuals should be analysed.

2.4.1. Obtaining behavioural information

Depending on the housing development to be assessed, several methods of defining behaviour relating to resource use may be applicable. If the housing development and occupants already exist, analysis of individual occupants can be performed. In such cases, questionnaires (or other forms of information gathering such as interviews) can be used to determine occupants' preferences and practices relating to their resource usage, their beliefs and goals, as well as their social practices and networks. This information can then form the basis for a behavioural typology, and social structure of the housing development's occupants can be quantified as a series of rules for modelling based on sociological or psychological decision theory (Amblard et al., 2001).

Another option of quantifying behavioural effects on resource usage is to use currently available sociological and resource use data from census collector districts or other area specific surveys (Melhuish et al., 2002). These data sets can be used to create synthetic distributions of resource use typical of the area's population. Further analysing these general resource use distributions with respect to socio-economic data can provide a good sample of what resource use relating to behavioural differences can be expected in the housing development.

The information obtained from these behavioural analyses can be integrated into the six interrelated models (water, CO_2, waste, ecosystem health, economic and social) as an initialisation point and driving mechanism to induce resource use changes for each model.

2.5. Multi-agent system modelling

In order to represent the six interrelated models in Figure 2, a suitable modelling platform is required. Multi-agent systems (MAS), an object-oriented programming method that was traditionally used for artificial intelligence applications, can be used to combine the water, CO_2, waste, ecosystem health, economic and social models, and their relationships to human behaviour, for temporal sustainability assessment.

It has been recognised by many authors that multi-agent based simulation has many advantages over techniques currently used to model complex systems (Huigen, 2003). Multi-agent systems have the capability to explicitly incorporate human behavioural, spatial and temporal aspects into a more holistic model (Waddell and Ulfarsson, 2004). They can also incorporate both qualitative and quantitative data in the same model (Taylor, 2003), unlike many other modelling tools. This is of particular use in the field of sustainability assessment. The sustainability goals, or long-term objectives for resource use in housing developments, can be included in the framework of the multi-agent system as "goals" or "beliefs" of the agents (Krywkow et al., 2002). The representation of human interaction processes, such as decision-making and learning based on changes witnessed in the surrounding environment, can be programmed into the individual agents in order to allow policy makers to examine the total resulting system behaviour (Moss et al., 2000).

2.5.1. Housing development multi-agent representation

In the complex housing development systems to be assessed, each occupant or household can be modelled as an "agent" that uses resources in the development "environment" and can communicate with other occupant "agents", as shown in Figure 7.

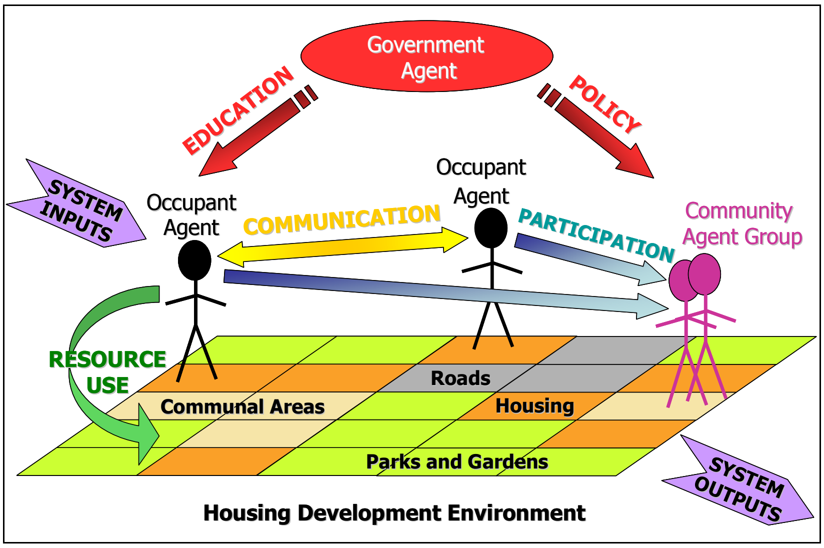

Figure 7: Multi-agent representation of a housing development

In the multi-agent representation of the housing development system shown in Figure 7, housing occupants can occupy the environment "cells" (a cell being one unit of the multi-agent model's spatial environment), interacting with the environment through resource use. The information for each house relating to its infrastructure, location and occupants can all be included in the cells' information. Using a multi-agent systems (MAS) approach, occupants can communicate with each other, exchange information and learn via community participation and interaction with other occupants. The households or "occupant" agents will also be able to store specific personal information on each of the agents, such as their beliefs, needs and decision processes. The government can also be created as an agent who can exert an influence on the housing development's occupants and environment through policy change and education programs. The five resource use models linked to the occupant behaviours can be incorporated directly into the multi-agent model using any number of readily available multi-agent modelling platforms, including: CORMAS (Common-pool Resources and Multi-Agents Systems); REPAST (REcursive Porous Agent Simulation Toolkit); and the DIAS/FACET (The Dynamic Information Architecture System / Framework for Addressing Cooperative Extended Transactions) platforms (ECAABC, 2004).

2.5.2 MAS for sustainability assessment and scenario analyses

After developing a multi-agent based model of the housing development that incorporates all of the resource models and the behavioural typology and interactions of the occupant agents, the model can be run over a desired number of time-steps (potentially weekly, monthly or seasonally following the discussion in Daniell et al. (2004c)) to examine the emergent behaviour of the housing development system. Simulations of the multi-agent model can also be run to assess the impacts of various changes to the system, scenarios or policy “options”, and their impacts on the emergent behaviour of the housing development system and relative sustainability.

2.5.3 Model validation

Multi-agent models can be validated, at least in the preliminary time-steps of simulation, using a variety of methods including the use of role playing exercises, questionnaires and forums (El-Fallah et al., 2004). Such methods can be used when the occupants of the housing development are willing to participate in the modelling process by either re-enacting the processes that take place in developments through games designed by the modeller or by answering questions to match the processes and attributes required for the multi-agent model. Other forms of validation for multi-agent models can include more qualitative methods of assessment such as determining whether each output relates to what is seen in reality in similar housing developments, and by comparing relationships and trends obtained, to trends found in literature. Considering the complex nature of the systems being examined, it is highly advantageous to validate each relationship used in the modelling process before all the relationships are combined, which has been termed “internal verification” (Vanbergue, 2003). As the use of multi-agent modelling for analysis of human ecosystems and natural resources management is still in its infancy, strict protocols for their validation are yet to be established. It is suggested that until such validation protocols are determined, modellers should use their common sense in determining the accuracy of their results, even after preliminary validation exercises have occurred (Bousquet et al., 1999).

Once validation of the multi-agent model has taken place, further simulations of the model may be performed to assess the sustainability of the housing development in its current state and in a range of other scenarios. For each simulation, the sustainability indicators chosen for each of the inner models of the multi-agent model can be obtained on a common Sustainability Scale. At this point, a total assessment of the housing development’s sustainability can be determined by an analysis of the collection of indicators.

3. Case study application

3.1. Introduction

To demonstrate how the methodology proposed in this paper can be applied in practice to assess the sustainability of housing developments, the Christie Walk housing development was used as a case study.

The Christie Walk housing development, located in the Central Business District of Adelaide in South Australia, is a medium density urban housing development made up of 14 varied dwelling types (straw-bale cottages, aerated concrete and rammed earth construction) with other aspects of “resource sensitive urban design” (Daniell et al., 2004b). These aspects include: water sensitive urban design; passive design of buildings to maximise energy savings; an inner-city location in close proximity to services; and designated community spaces (Downton, 2002).

Christie Walk is considered as a leading example of sustainable development due to the innovative nature of its design. However, until now, verification of this claim has been difficult. The nature of its design, combined with the accessibility of data, made Christie Walk an appropriate case study with which to test the proposed methodology presented in Section 2 of this paper.

3.2. Christie Walk system and multi-agent representation

The first step of the assessment requires the system and system boundaries to be carefully defined, as outlined in Figure 1. As with any complex system, this is not necessarily a straightforward task since Christie Walk currently relies upon numerous systems outside its spatial boundaries. For the development to be sustainable it must be able to meet its requirements without compromising the ability of adjacent (or external) systems to be sustainable. The system boundary for the assessment of Christie Walk was considered to be its spatial boundaries (fence line). Any resource use sourced exterior to the system was considered to be unsustainable as this allows the development to manage its own resources and minimises any impact on adjacent systems’ ability to be sustainable. The Adelaide metropolitan area was chosen as the larger system providing the resource use comparisons against the resource use of Christie Walk.

An analysis of the system, its resources and their interactions enabled detailed models representing the processes within the system to be developed as the second step of the assessment process. Models were developed for water, CO_2, waste, economic and social processes. However, it was considered unnecessary to include an ecosystem health model. Christie Walk is in the central business district of Adelaide and the site was previously used for commercial purposes with little to no biodiversity on the site. Any positive impact of improving the biodiversity on the site is considered as sustainable (and thus not quantified on the Sustainability Scale). Improvements in biodiversity may be shown through increased quality of life, which is processed through the social model. Similarly, other air quality and water quality factors not included in the ecosystem health model could be partially taken into consideration in the social model.

The graphical interpretation of the models, specifically for the Christie Walk development, is given in Figures 8-12. Further explanation on each of the models can be found in Daniell et al. (2004c).

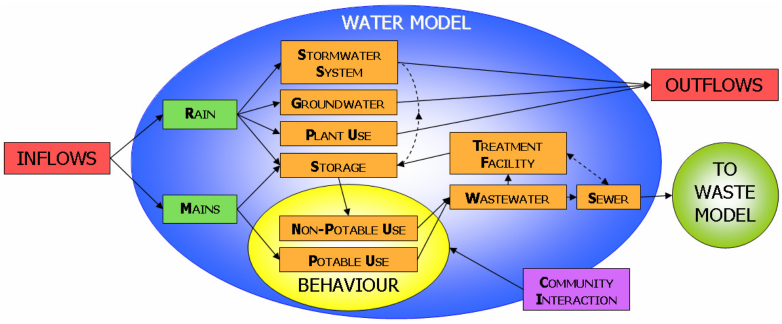

Figure 8: Christie Walk water model conceptualisation

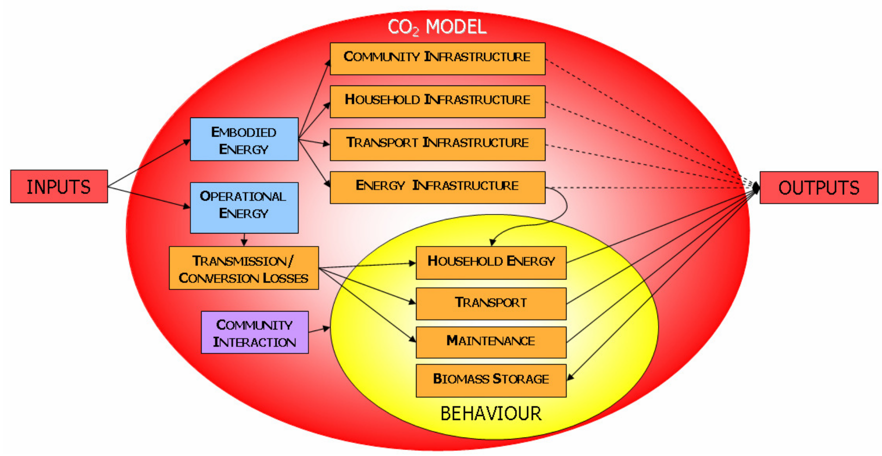

Figure 9: Christie Walk CO_2 model conceptualisation

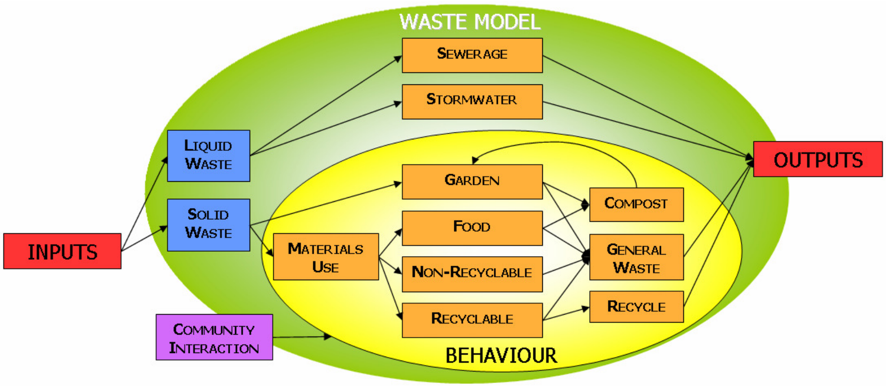

Figure 10: Christie Walk waste model conceptualisation

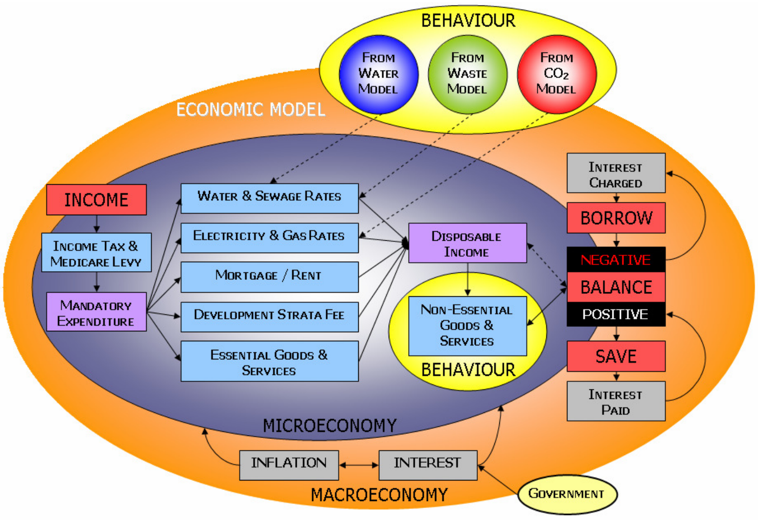

Figure 11: Christie Walk economic model conceptualisation

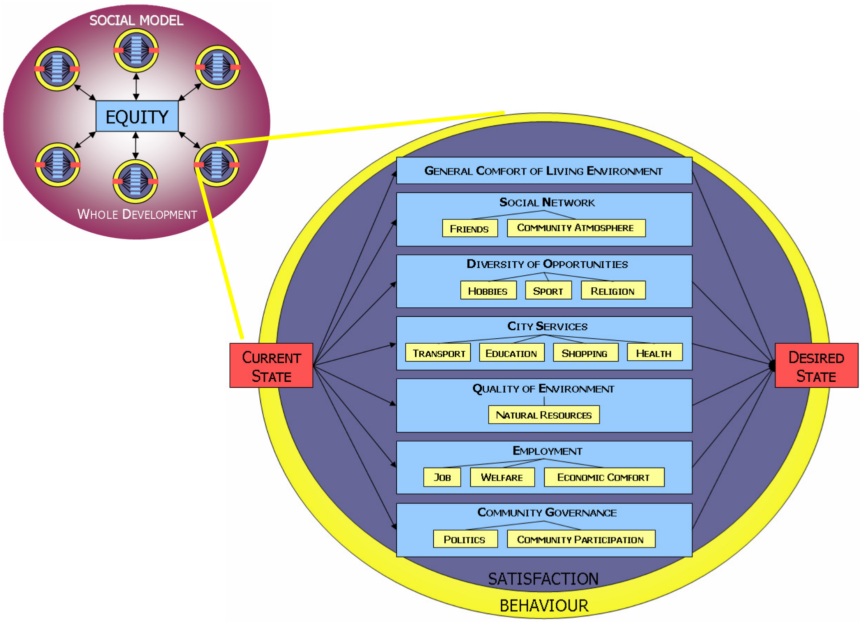

Figure 12: Christie Walk social model conceptualisation

A sustainability indicator for each of the water, CO_2, waste, economic and social models created for the Christie Walk housing development was then chosen as the next step in the methodology as shown in Figure 1. These indicators and the equivalent measures used in the construction of the Sustainability Scales are presented in Table 1.

Table 1: Model sustainability indicators

Model	Sustainability Indicator	Equivalent Measure
Water	mains water use, $x_w(t_j)$	litres / person / day
CO_2	mass of equivalent CO_2 , $x_c(t_j)$	tonnes / person / year
Waste	waste sent to landfill, $x_l(t_j)$	kg / person / week
Economic	average % usage of available household debt, $x_d(t_j)$	% usage of available debt
Social	equitable satisfaction level, $x_s(t_j)$	equitable satisfaction level

3.3. Defining behaviour

Behaviour for the Christie Walk occupants was defined using two methods based on those described in Section 2.3.1. The first method was to examine the occupants' preferences and practices relating to resource usage, their beliefs and goals, and their social practices and networks through the use of a survey which was distributed to all Christie Walk residents. The second method was based on examining currently available sociological and resource use data in order to quantify the behavioural aspects of the Christie Walk occupants with respect to their resource use patterns, in comparison with the resource use of residents in the larger metropolitan Adelaide area.

The surveys distributed to the Christie Walk residents were used to obtain behavioural data regarding the occupants' values, preferences, practices and social interactions in a range of domains related to resource utilisation and other aspects of the five models described in Section 3.2. For the water, CO_2 and waste models, the resource use distributions created for the metropolitan Adelaide area were used in conjunction with the survey information to assign general behavioural classifications to each household. In order to demonstrate the procedure for behavioural classification of occupants, the example of waste production will be outlined.

From the responses to the waste related questions in the survey, the behavioural profile of the occupants, relating to both quantity of waste produced and the amount of this waste they are likely to recycle, were assessed. From these profiles, each occupant was assigned a grouping from the cumulative distributions of waste production and percentage waste diversion in the metropolitan Adelaide area. To simplify the process used in this case study, each distribution was only broken down into three levels of behavioural classification of resource usage (33 percentile sections of the population). The cumulative distribution for total waste production in the Adelaide metropolitan area is shown with these waste production level groupings in Figure 13.

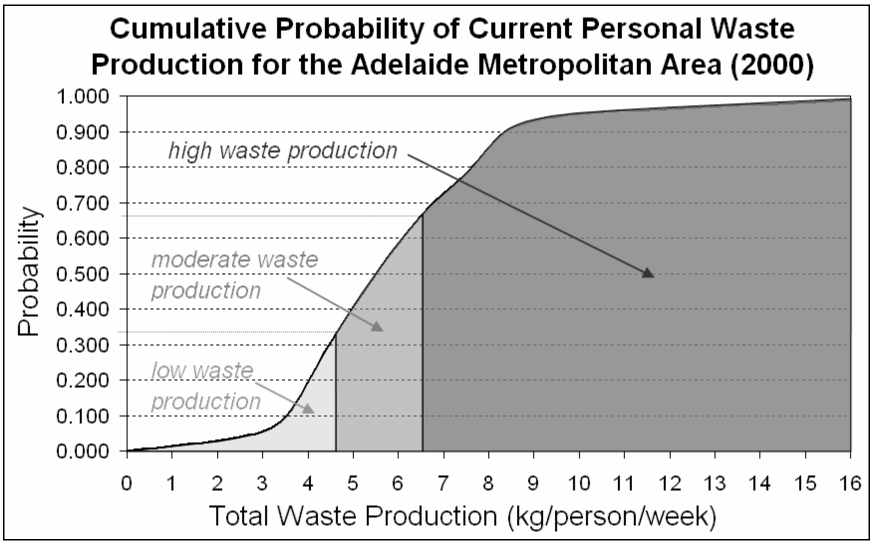

Figure 13: Occupant behaviour categories for total waste production

This division into behavioural categories enables the occupants' waste production to be assigned randomly in the multi-agent model from the appropriate category at each iteration. This allows the waste produced to fluctuate much like weekly household waste production in reality. Behavioural classifications for the other resource practices (for recycling, energy use, transport, water use and financial use) were formulated in the same way for the Christie Walk residents compared to the larger metropolitan Adelaide area.

3.4. Multi-agent model implementation

The multi-agent modelling platform, CORMAS (COmmon-pool Resources and Multi-Agent Systems), which uses the SmallTalk programming language, was used in order to combine all the required models and behavioural information for the sustainability assessment of Christie Walk. This modelling platform was developed by the French *Centre de Coopération Internationale en Recherche Agronomique pour le Développement* (CIRAD) in Montpellier, specifically for modelling the relationships between societies and their environments for natural resources management (Bousquet et al., 1998). This particular platform was chosen as it is freely available and has a strong support network to help with any problems experienced with programming or the software.

Representation of the Christie Walk system in CORMAS was performed in several stages: representing the "environment"; representing the "agents"; and representing the models and interactions. After the model was created, it was calibrated, tested and validated before operational use.

The CORMAS platform allows for a spatial representation of a system as a grid of cells or “spatial entities”. Each of these “spatial entities” can have attributes such as area or land use, as well as processes such as rainfall or vegetation growth. For the purposes of the model, a grid was devised to mimic the land use pattern of the Christie Walk development, including the land use types of unit (house), garden, path/vegetation, car park, waste treatment plant and bike shelter. From the architectural plan drawings of Christie Walk, the conversion to the model environment is shown in Figure 14.

Figure 14: Architectural plan of the Christie Walk development and the CORMAS model environment representation

One agent was initialised per household with behavioural categories as outlined in Section 3.3, which could be graphically represented on the CORMAS model environment (in Figure 14 as pentagons in each home unit). Each agent was also pre-programmed with a specific behavioural category of community interaction which was determined from the surveys and interviews with residents.

The five models previously defined in Section 3.2 (water, CO_2, waste, economic and social) and other processes for the Christie Walk model were written on several levels within the CORMAS platform. Methods relating to household resource use were written at the household level, for example in-house water use, energy use, transport use, financial use and individual social sustainability. Other methods that related to the overall housing development situation were run at the main model level, for example the development’s water use and the five sustainability indicators. At the government level, the methods for updating the interest rates and corresponding inflation rates, CPI, wages and tax brackets were performed. The full list and location of model methods is documented in a linked UML diagram.

A seasonal time-step (three months) was chosen for the model in order to ensure reasonable computational efficiency, as well as allowing seasonal variation to be gauged.

The model was validated to the greatest possible extent using several of the methods outlined in Section 2.5.3, including internal verification (i.e. checking individual model outputs such as water and energy use against known meter readings), survey responses and general matching of the model outputs with observations of real-world housing developments.

3.5. Results of sustainability assessment simulations

Following the construction and validation of the CORMAS multi-agent Christie Walk model, simulations were run over a 30 year period with the sustainability indicators prescribed in Table 1 for the water, CO_2, waste, economic and social models being rated using the Sustainability Scale framework outlined in Section 2.4.

A simulation of the Christie Walk multi-agent model over a 30 year simulation period assuming relatively stable economic, political and climatic conditions is illustrated in Figure 15, showing the five model indicators against the SSRs.

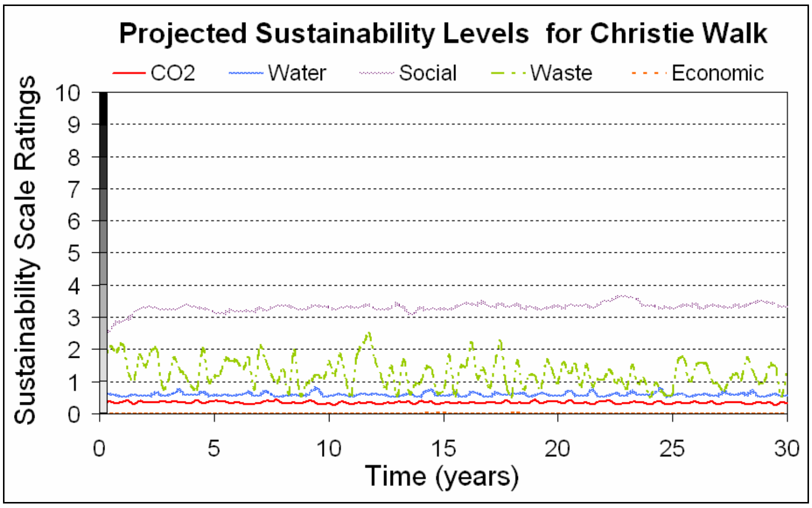

Figure 15: Sustainability Scale Ratings for Christie Walk for the five indicators

Sustainability indicators of mains water use, waste sent to landfill and CO_2 production, are all based on distributions of the indicator variables within the metropolitan Adelaide area, according to the framework presented in Section 2.4. It can be seen that for each of these indicators in Figure 15, Christie Walk is well within the lower 30th percentile of resource users in the Adelaide metropolitan area that exhibit unsustainable resource use. This demonstrates the effectiveness of some of the components integrated into the Christie Walk housing development design, when compared to other Adelaide residential developments.

As the modelling process adopted is stochastic, every simulation performed will vary within reason. Outputs from each of the simulations give an overview of possible trends in the variation of the sustainability indicator ratings. These indicator ratings may be used to target specific areas for improvement and further analysis by government and planning authorities.

This simulation of the Christie Walk model through time reinforces the notion that the sustainability of a housing development will vary due to many parameters, including behavioural and climatic variation. For future government planning and assessment applications of this framework, both extreme and average Sustainability Scale values should be considered when such results are to be used for decision making.

3.6. Scenario analyses

One of the greatest advantages of multi-agent modelling is the capability to perform "what-if" scenario analyses. Using the Christie Walk model, a variety of scenario analyses were undertaken during the course of this research, including assessment of the effects of droughts, changes to building materials, location, behaviour and community interaction on the sustainability of the Christie Walk development. The full analysis of these scenarios is given in Daniell et al. (2004c). For this paper, the question of whether occupant behaviour is closely linked to the sustainability of housing developments will be examined.

3.6.1. Behaviour scenarios

The effect of human behaviour on natural resources utilisation is largely recognised, but rarely quantified (Curwell and Hamilton, 2003). Decision makers such as governments and planning authorities have the ability to influence people's behaviour through legislation, education, increased awareness, information sharing, and price manipulation. However, the effectiveness of such campaigns has previously been difficult to analyse.

In order to analyse if occupant behaviour has a significant impact on the sustainability of Christie Walk, several scenarios were run, specifically focussing on waste production, recycling, water and energy use. In each case, high, moderate and low levels of each resource behaviour (see Figure 13) were initialised for all residents in the CW model and run for a 30 year simulation. These results were also compared to results for the current Christie Walk occupants (shown by "CW" on the graphs). All other behavioural patterns were kept constant at the Christie Walk levels when an individual behavioural characteristic was analysed.

Figure 16 shows the effect of different behavioural levels of total waste production (total quantity of waste that needs to be reused, recycled, composted or disposed of to landfill) on the waste sustainability of a housing development (quantity of waste sent to landfill).

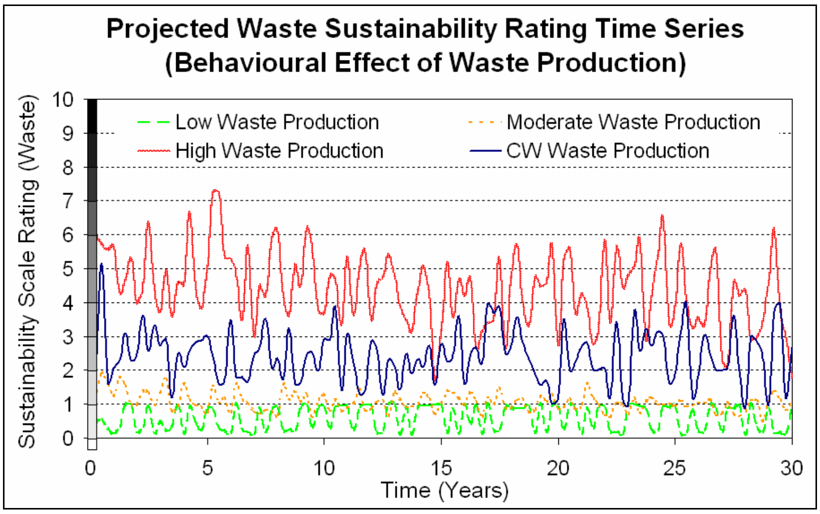

Figure 16: Effect of waste production behaviour on waste sustainability

It can be seen from Figure 16 that the effect of total waste production behaviour on the waste sustainability of the housing development is substantial. Occupants with high waste production have Sustainability Scale Ratings as high as 7.3, while occupants with low waste production approach the threshold level for waste sustainability. A similar pattern, although with an improvement in ratings, is also observed for the behavioural effect of recycling on the amount of waste sent to landfill in Figure 17.

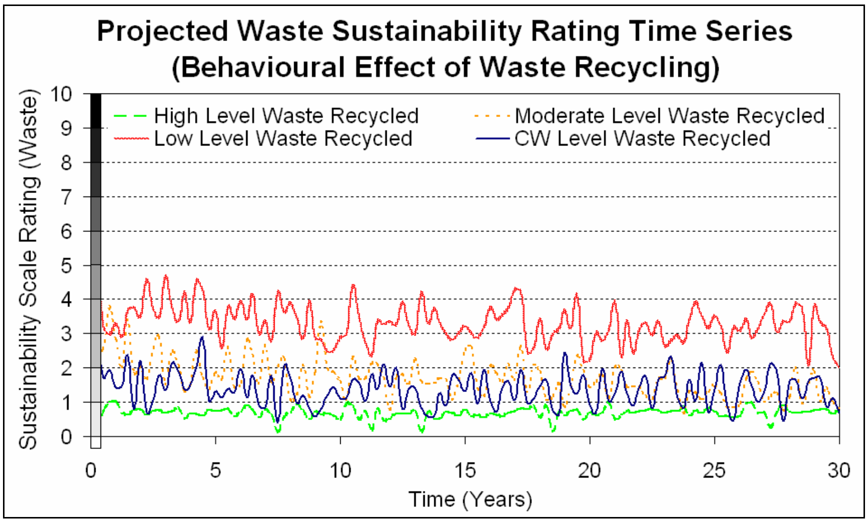

Figure 17: Effect of recycling behaviour on waste sustainability

These results show that both minimising waste at the source and recycling behaviour can have a significant effect on waste sustainability. It must also be noted that these results show that even with the worst recycling behaviour, the infrastructure at the Christie Walk development, including composting and recycling services, helps to reduce the effect of behaviour to below the 50th percentile of the greater Adelaide population.

A significantly different pattern is seen in Figure 18 for the effect of water use behaviour on water sustainability (based on mains water use) in Christie Walk.

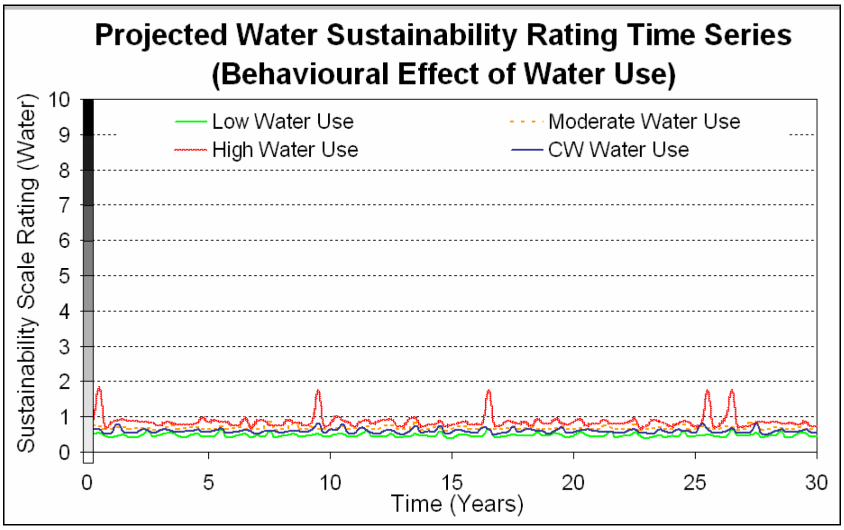

Figure 18: Effect of water use behaviour on water sustainability

In this case, Sustainability Scale Ratings (SSRs) for water use show the effects of behaviour to be quite insignificant within the Christie Walk development. Figure 18 shows an average difference in water SSRs of less than 0.4 between low and high water use. This indicates that in the Christie Walk development, behaviour has very little effect on water sustainability compared to the rest of metropolitan Adelaide water users. This is thought to be predominately due to the inclusion of water saving devices and the use of stormwater for toilet flushing and garden watering, which reduces the overall mains water use in the housing development. Changes in behaviour therefore do not have the effect they might have in developments without water saving infrastructure or small gardens.

The behavioural effects relating to in-house energy use on the CO_2 Sustainability Scale Ratings in Figure 19 show similar results to the water use behaviour example.

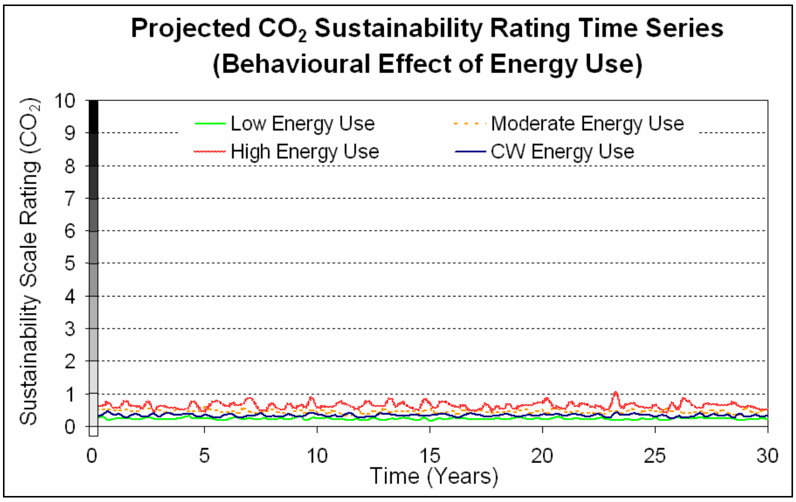

Figure 19: Effect of energy use behaviour on CO_2 sustainability

Once again, the small spread of SSRs indicates that in the Christie Walk environment, behavioural influence on energy use has very little effect on sustainability. Due to the inclusion of energy efficient appliances, solar hot water heaters and building materials with high thermal efficiency, which leads to a lack of air conditioners, energy use in Christie Walk remains at very low levels for a range of behavioural types compared to metropolitan Adelaide users.

3.6.2. Discussion of behavioural results

The results of the behavioural analyses showed that for certain household factors such as total waste production and waste recycling, changes in behaviour could significantly influence sustainability. Christie Walk includes basic infrastructure to encourage occupants to recycle and compost waste. However, because of their latent effectiveness, the infrastructure and design of other components of the development such as water infrastructure and passive building design, are seen to drastically reduce the potential impacts of residents' behaviour on Christie Walk's sustainability.

These findings highlight the importance of good design and infrastructure in achieving sustainability in built environments. Although it is possible for governments and planners to potentially have an influence on occupant behaviour, it has been shown that attempts to change behaviour can be very difficult, time consuming, and often met with extreme opposition. It could therefore be more effective for governments and planning authorities to concentrate on the improvement of infrastructure which will lead to a reduction in the effect of human behaviour.

From the information obtained from the survey and the knowledge of the practices at Christie Walk, it was found that most residents had a high waste diversion to recycling (i.e. they recycled large percentages of the waste they produced, rather than disposing of it to landfill. Many residents had a low waste production, although it was interesting to note that quite a number of residents exhibited a moderate waste production, seeming to focus more on the reduction of their waste going to landfill through recycling, as opposed to the minimisation of waste generation (i.e. buying foods with less or no packaging etc.). It could therefore be advantageous to focus any future education campaigns on buying produce with less packaging rather than focussing on the end solution of recycling.

From the results of the survey of Christie Walk residents, it was also found that community interaction can have a significant impact on improving resource use behaviour (although not comparatively as large as the impacts of infrastructure and design), especially on recycling and energy usage, and to a lesser extent on water usage and waste minimisation. These findings highlighted that if it is not possible to improve infrastructure, then improvements to resource use through certain community programs can be achieved. It has been stated by Marks et al. (2003) that the most effective way to introduce behavioural change is by including communities in the decision-making processes from the beginning of any plans for change. In this way, resistance can be reduced and the eventual uptake of practices and changes in behaviour can thus be made more quickly and smoothly.

4. Conclusions and future directions

The new methodology presented in this paper allows a housing development to be examined as a complex system rather than being broken down into components. It also provides a method of assessing the sustainability of a housing development through time using multi-agent based simulation. The multi-agent framework allows the integration of interrelated models including: water; CO_2; ecosystem health; waste; economic; and social; as well as their respective sustainability indicators. The methodology assists policy and decision making within governments and planning authorities by examining and comparing the quantitative sustainability of housing developments using Sustainability Scale Ratings. The assessment process allows different indicators of sustainability to be compared on a common scale (i.e. water and waste can be directly analysed for their comparative sustainability) or indicators in different housing developments can be compared. Furthermore, simulations of the multi-agent based housing development model can be used to examine the emergent behaviour of the housing development system for various system changes and “what-if” scenarios along with the corresponding sustainability assessment of the indicators on the Sustainability Scale. This methodology would provide an ideal decision support system for stakeholders interested in urban developments, particularly in policy and planning applications.

The methodology, shown to be operational in the case study application of the Christie Walk housing development, simultaneously overcomes identified deficiencies in existing assessment tools, specifically the inadequate inclusion of behavioural, spatial and temporal aspects within the sustainability assessment of complex housing development systems.

Results from the Christie Walk case study with its many components of resource sensitive urban design showed that the development compared favourably to the rest of the Adelaide metropolitan area. The importance of good infrastructure and design in reducing the impacts of human behaviour on housing development sustainability were also highlighted through the behavioural scenario analyses.

From the success of this study, it is considered that the methodology outlined in this research could be applied to assess other developments throughout the world for comparative purposes or as part of planning and policy assessment. It could equally be used as part of a participatory framework for decision-making and to stimulate stakeholder discussions relating to sustainability agendas.

Future directions for this research are numerous and could including the following:

- Further analysis of methods to model occupant behaviour based on more complex decision theory, game theory or other sociological and psychological theory;
- Further analysis of the impacts of resource pricing on usage and behavioural changes;
- Studies of behaviour relating to the uptake of sustainable technologies and practices, and how policy makers can better work with communities to ensure a successful uptake of such technologies and practices; and
- Expansion of the methodology to assess the sustainability of rural systems, companies, countries, or any other complex system, potentially with the integration of Graphical Information Systems (GIS).

5. Acknowledgements

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